Project X and the Future of the Fermilab Accelerator Complex

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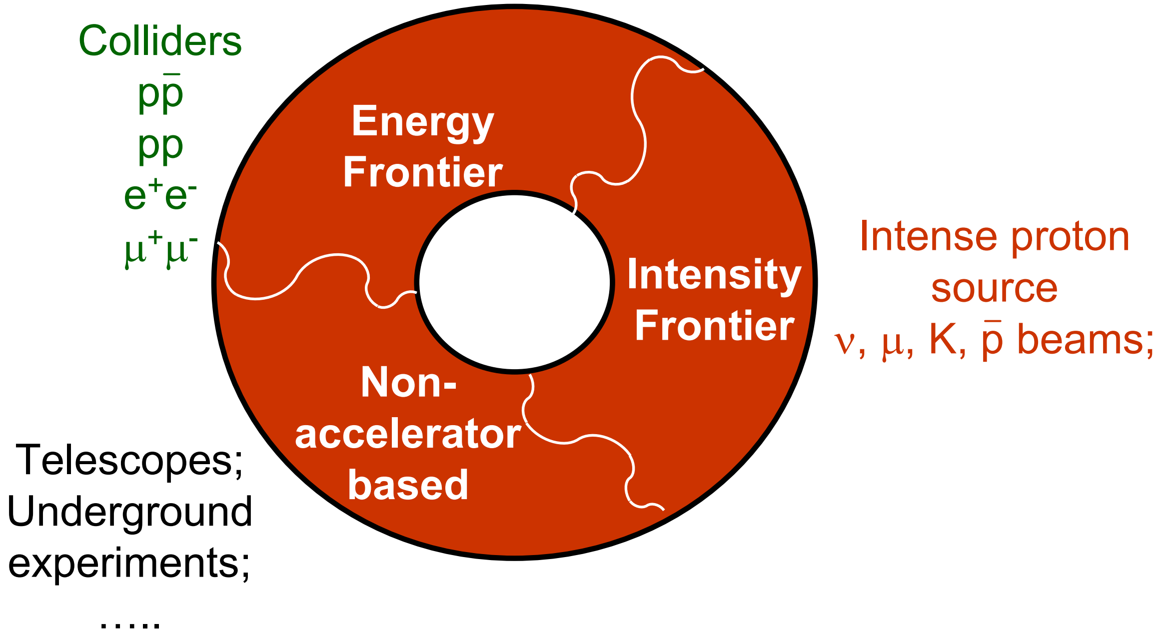
Outline

- Strategic Context
- Project X Facility Overview
- Project X Research, Design, and Development Plan
- Project X and Other Future Facilities

Strategic Framework

- Fermilab is the sole remaining U.S. laboratory providing facilities in support of accelerator-based Elementary Particle Physics.
- The Fermilab long-term plan incorporates three strategic directions:

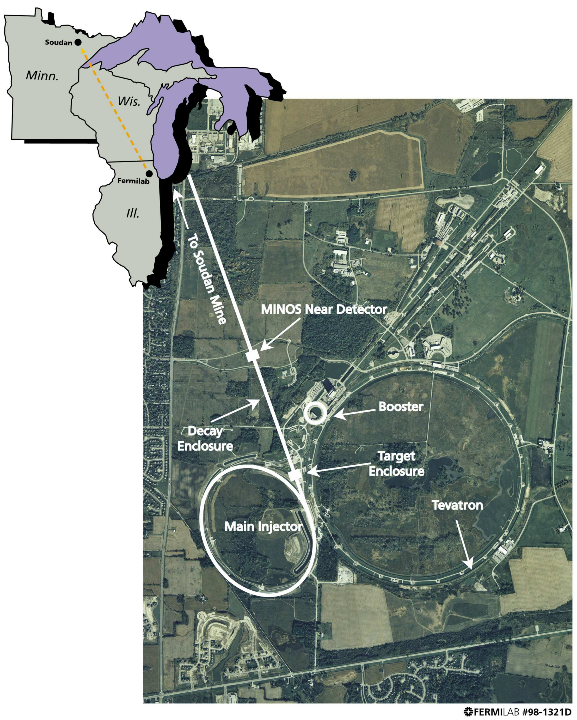


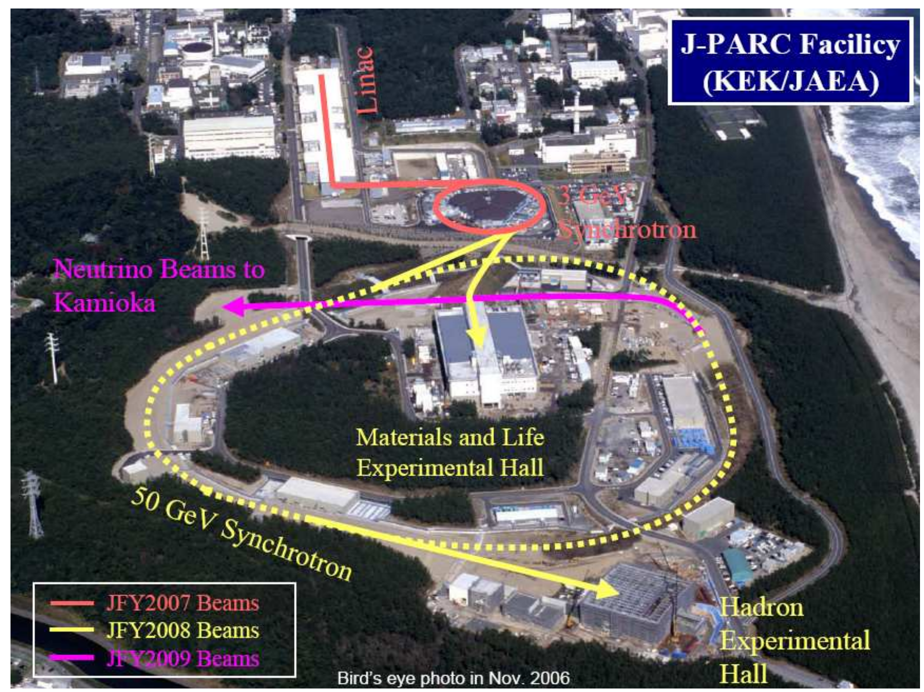
Strategic Framework
Role in the World Program

- Energy Frontier: Fermilab has operated the highest energy particle accelerator in the world, the Tevatron, since 1983. . .
  – We will be supplanted by Large Hadron Collider (LHC) sometime in the next 12 months

Strategic Framework
Role in the World Program

- Intensity Frontier: Fermilab currently operates the world's most advanced long-baseline neutrino program. . .
  – J-PARC will become competitive in 2009 - 2010





Strategic Framework
Planning for the Future

In March 2007 Pier Oddone, in coordination with HEPAP, established a "Steering Group" to develop a strategic plan for EPP in the U.S.

- Focus on accelerator based elementary particle physics
- Membership drawn from both Fermilab and national communities
- Chaired by Young-Kee Kim (Fermilab Deputy Director)
- Report issued September 2007
  http://www.fnal.gov/directorate/Longrange/Steering_Public/
- The report has been accepted by Fermilab management as representing our strategic plan for the future, and is a primary input to the P5 process that is currently ongoing.

Strategic Framework
Planning for the Future

Fermilab Steering Group Charge:

Develop a strategic roadmap for the evolution of the accelerator-based EPP program, focusing on facilities at Fermilab.

- Provide discovery opportunities in the next two to three decades
- Keep the construction of the ILC as a goal of paramount importance
- Consistent with prior recommendations of EPP2010 and P5

Strategic Framework
The Fermilab Roadmap

- Fermilab's highest priority is discovering the physics of the Terascale by participating in LHC, being one of the leaders in the global ILC effort, and striving to make the ILC at Fermilab a reality.
- Fermilab will continue its neutrino program with NOνA as the flagship experiment through the middle of the next decade.
- Scenario 1 (ILC construction near the GDE proposed timeline)
  - Fermilab will focus on the above programs
- Scenarios 2 & 3 (ILC delayed)
  - Fermilab should extend our neutrino and flavor physics opportunities by upgrading the proton accelerator complex.
  - Modest delay $\Rightarrow$ SNuMI
  - If ILC delay would accommodate an interim major project $\Rightarrow$ Project X

Strategic Framework:
The Fermilab Roadmap

- Scenario 4 (ILC constructed off-shore)
  - Do SNuMI at a minimum.
  - Do Project X if resources are available and ILC timing permits.
- In all scenarios,
  - Provide support of Project X R&D starting now with emphasis on:
    - expediting R&D and industrialization of ILC cavities and cryomodules
    - overall design of Project X (by 2010)
  - increase R&D for future accelerator options concentrating on neutrino factory and muon collider.
  - support detector R&D for effective use of future facilities

Strategic Framework
The Fermilab Roadmap and P5

- P5 is currently preparing a strategic plan that is meant to be robust under a variety of (financial) conditions.
- The plan is being produced under assumptions that lead one to believe we are not in Scenario 1.
- In support of the P5 process Fermilab prepared and presented a Project X Research, Design & Development Plan.

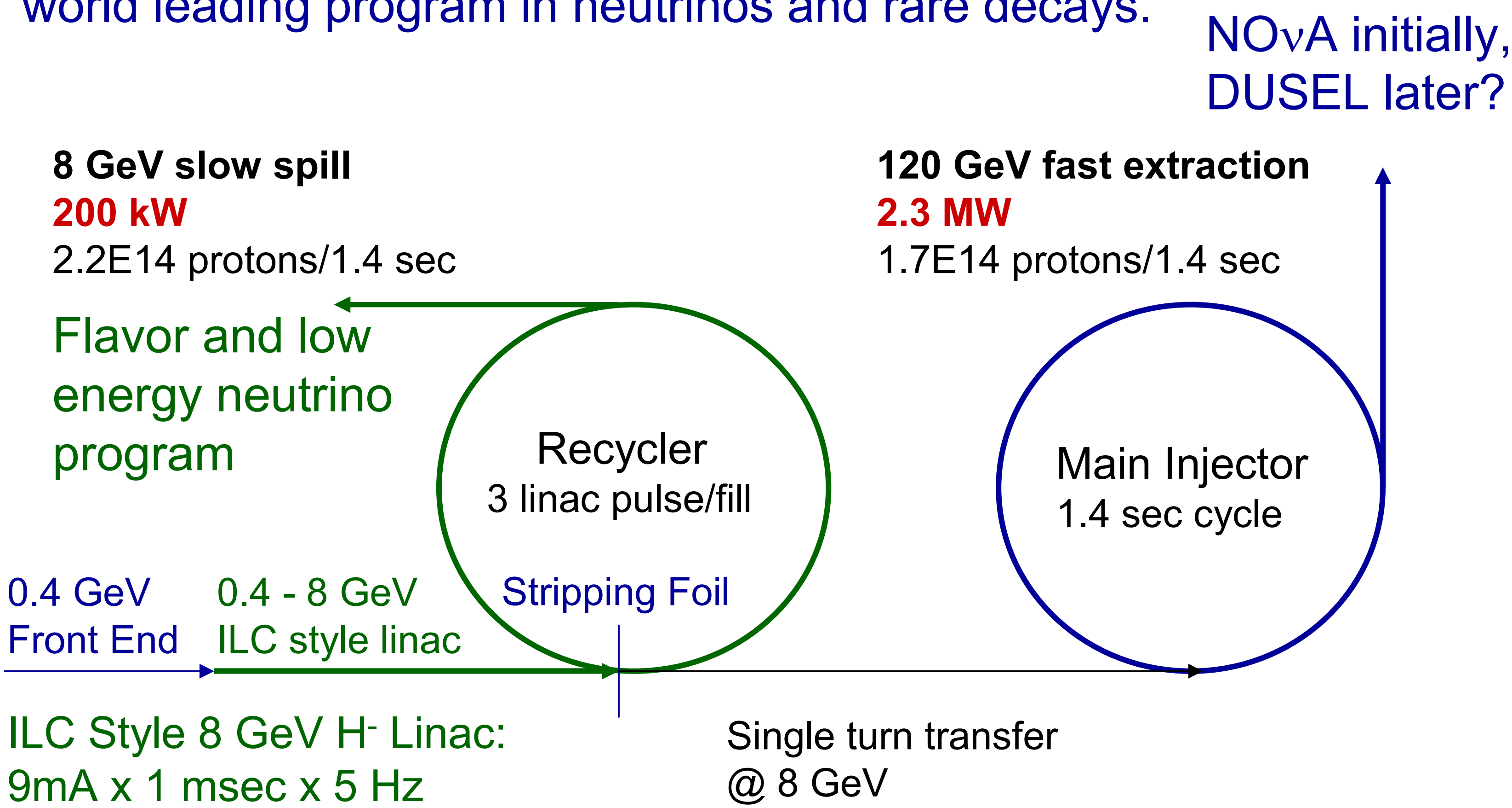
  http://projectx.fnal.gov/RnDplan/R&D%20Plan_Rev3.2.doc

- P5's recommendations should become publicly known at the HEPAP meeting scheduled for the end of May.

  $\Rightarrow$ **We hope for/expect strong support for Project X from P5**

Project X Facility Overview

Project X is a high intensity proton facility aimed at supporting a world leading program in neutrinos and rare decays.



Project X Facility Overview
Scope

- The Research, Design & Development (RD&D) plan includes:
  - A new 8 GeV, superconducting, H^- linac capable of delivering 360 kW of beam power;
  - A new beamline for transport of 8 GeV H^- from the linac to the Recycler Ring;
  - Modifications to the Recycler required for 8 GeV H^- injection, accumulation, and delivery of protons to the Main Injector;
  - Modifications to existing beamlines to support transfer of 8 GeV protons from the Reycler to the Main Injector;
  - Modifications to the Main Injector to support acceleration and extraction of high intensity proton beams over the range 60-120 GeV;
  - Modifications to the NuMI facility to support operations at 2 MW beam power;
  - Modifications to the Recycler to support a new extraction system for delivery of 8 GeV protons in support of a dedicated flavor program.

Project X Overview
High Level Performance Goals

Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Particles per pulse	5.6×10^{13}	
Pulse rate	5	Hz
Beam Power	360	kW
Recycler		
Particle Type	protons	
Beam Kinetic Energy	8.0	GeV
Cycle time	1.4	sec
Particles per cycle to MI	1.7×10^{14}	
Particles per cycle to 8 GeV program	2.2×10^{14}	
Beam Power to 8 GeV program	206	kW
Main Injector		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per cycle	1.7×10^{14}	
Beam Power at 120 GeV	2300	kW

Project X

360 kW 8GeV Linac

19 Klystrons (2 types)
422 SC Cavities
55 Cryomodules

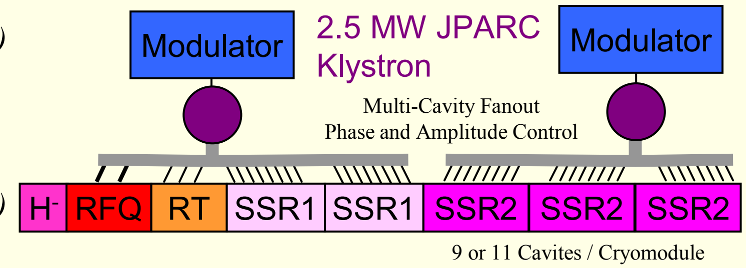
Front End Linac

325 MHz 0-10 MeV

1 Klystron (JPARC 2.5 MW)
16 RT Cavities

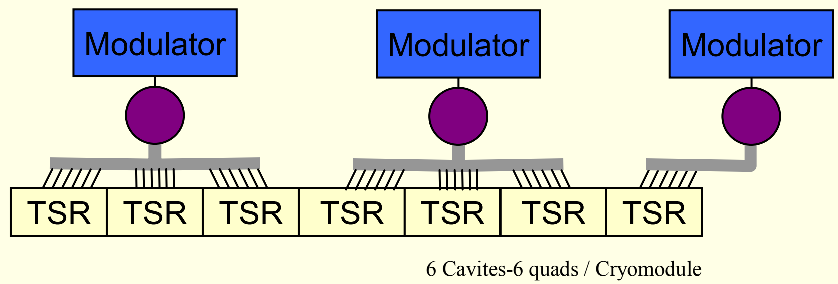
325 MHz 10-120 MeV

1 Klystron (JPARC 2.5 MW)
51 Single Spoke Resonators
5 Cryomodules



325 MHz 0.12-0.42 GeV

3 Klystrons (JPARC 2.5 MW)
42 Triple Spoke Resonators
7 Cryomodules



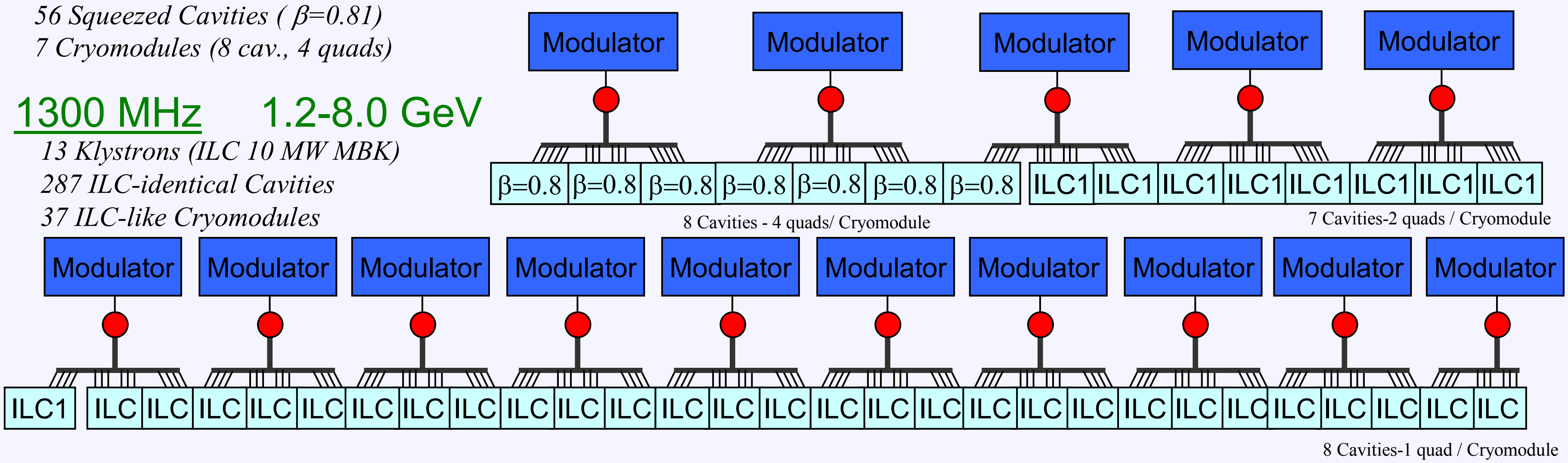
ILC LINAC

1300 MHz 0.42-1.2 GeV

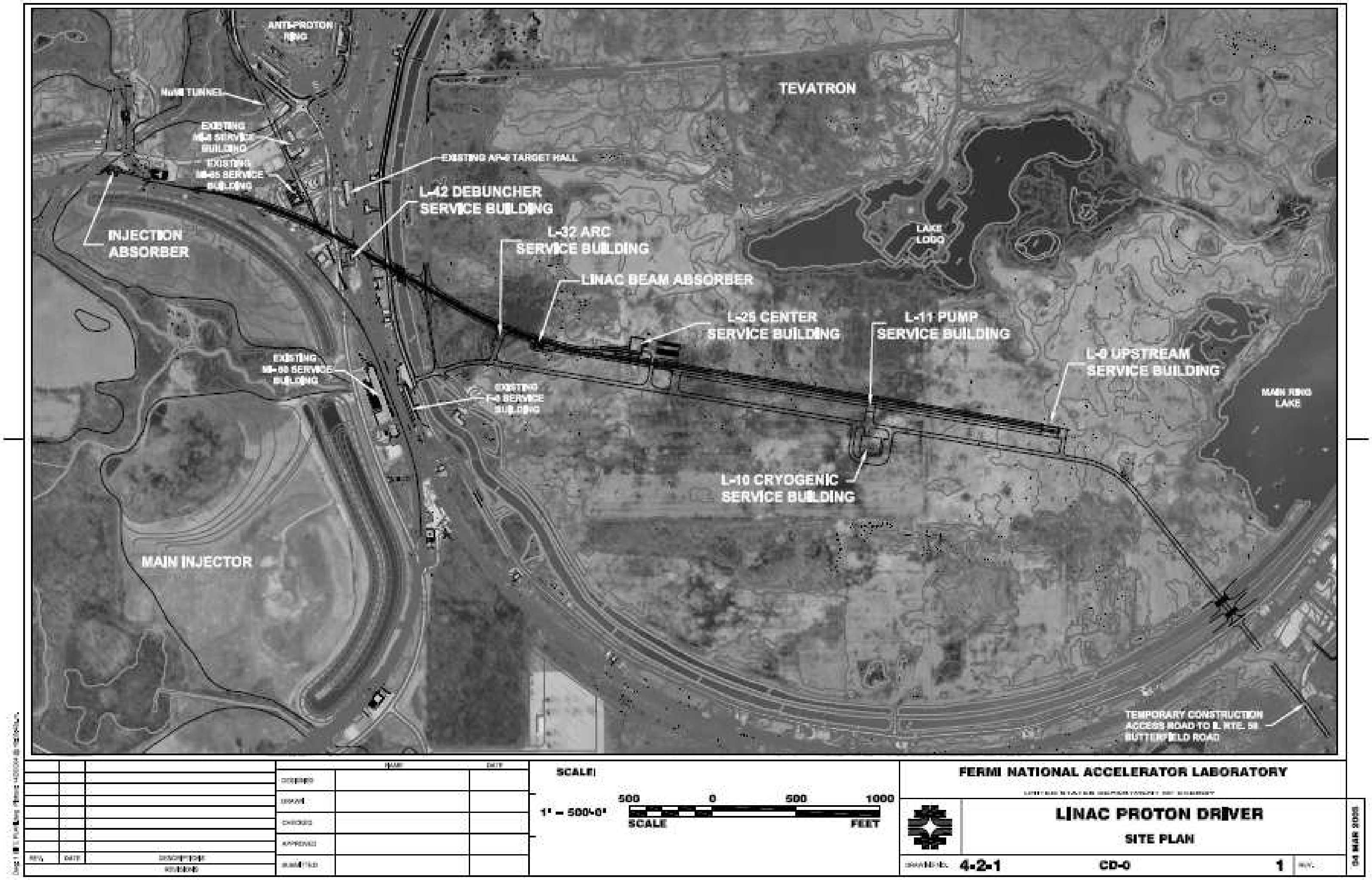
2 Klystrons (ILC 10 MW MBK)
56 Squeezed Cavities (β=0.81)
7 Cryomodules (8 cav., 4 quads)

1300 MHz 1.2-8.0 GeV

13 Klystrons (ILC 10 MW MBK)
287 ILC-identical Cavities
37 ILC-like Cryomodules



Project X Overview
Provisional Siting



Project X RD&D Goals
Program Goals

- The goal of the Project X RD&D program is to provide support for a Critical Decision 0 (CD-0) in 2009, leading to a CD-2 in 2011.
  – Design and technical component development;
  – Fully developed baseline scope, cost estimate, and schedule
  – Formation of a multi-institutional collaboration capable of executing both the RD&D plan and the follow-on construction project.
- The primary technical goal is a complete facility design that meets the needs of the US research program, as established via CD-0.
  – 2 MW of beam power over the range 60 – 120 GeV,
  – simultaneous with at least 100 kW of beam power at 8 GeV.

Project X RD&D Goals
Program Goals

- Alignment with the ILC and SRF programs:
  - Development of shared technologies to the benefit of both efforts
    - Cavity/cryomodule design, rf sources, e-cloud, civil infrastructure
  - Project X linac designed to accommodate accelerating gradients in the range 23.6 – 31.5 MV/m (XFEL – ILC)
    - Final design gradient determined prior to CD-2.
- Preliminary identification of performance upgrade paths based on muon facility requirements
  - 2-4 MW at 8 GeV

Project X RD&D Goals
Management/Organization Goals

- Formation of a multi-institutional collaboration to carry out the Project X RD&D program and to prepare a plan for construction.
- Development all project documentation and organizational structures required by DOE 413.3.
- Timeline:
  - 2008:
    - Initiate RD&D Program
    - Form Project X RD&D Collaboration
  - 2009: CD-0
    - Start project documentation (including CDR), and accompanying RD&D program
  - 2010: CD-1
    - Finish CDR, form collaboration to undertake construction project
  - 2011: CD-2
    - Establish project baseline (scope, cost, schedule)

Project X RD&D Strategy
Preliminaries

- Proton Driver Design Studies over 2002-2004
  - Director's Review in March 2005
- Project X Preliminary Report - August 1, 2007
  - Reviewed by Fermilab Accelerator Advisory Committee
    - "We congratulate the Project X team on an innovative design…The committee therefore very strongly supports the work that is planned for Project-X."

      http://projectx.fnal.gov/AACReview/ProjectXAacReport.pdf
- Project X Accelerator Physics and Technology Workshop - Nov. 12-13, 2007
  - 175 attendees from 28 institutions.

    http://projectx.fnal.gov/Workshop/ProjectXWorkshopReport.pdf
- Project X presentation to P5 – Jan. 31, 2008

http://www.fnal.gov/directorate/program_planning/P5/P5_Jan2008/Agenda.html

Project X RD&D Strategy
Technical Elements

- **Requirements** - develop major system requirements
  - Eight major systems
  - 17 base requirements
  - 68 derived requirements
- **Issues** - discuss issues arising from the requirements
- **Elements** - define the elements of an RD&D plan that
  - Addresses the issues arising from the requirements
  - Are directed towards a completion of Conceptual Design Report
- **Resources and Schedule** - estimate:
  - The resources required to complete the RD&D plan
  - The schedule required to complete the RD&D plan

Note: The Project X RD&D strategy assumes the existence of ILC, SRF, and HINS programs.

Project X RD&D Strategy

Project X Major Systems

- A front end linac operating at 325 MHz.
- An ILC-like linac operating at 1300MHz.
- An 8 GeV transfer line and H- Injection system.
- The Recycler operating as a stripping ring and a proton accumulator.
- The Main Injector acting as a rapid cycling accelerator.
- A slow extraction system from the Recycler.
- 120 GeV Neutrino beamline.
- Civil Construction and Utilities
- Controls

Project X RD&D Strategy

Major System Requirements

Req. No.	Description	Req.	Unit	Reference Requirements			
1.0	**General**						
1.1	120 GeV Beam Power	2.3	MW				
1.2	8 GeV Beam Power	360	kW				
1.3	8 GeV Slow Spill Beam Power	200	kW				
1.4	8 GeV Slow Spill Duty Factor	55	%				
1.5	120 GeV Availability	75	%				
1.6	8 GeV Availability	80	%				

Req. No.	Description	Req.	Unit	Reference Requirements			
2.0	**325 MHz Linac**						
2.1	Average Beam Current	9	mA	1.2			
2.2	Pulse Length	1	mS	1.2			
2.3	Repetition rate	5	Hz	1.2			
2.4	325 MHz Availability	98	%	1.6			
2.5	Peak RF Current	14.4	mA	2.1	2.11	2.13	2.14
2.6	Final Energy	420	MeV	3.6			
2.7	Energy Variation (rms)	1	%	3.10			
2.8	Bunch Phase jitter (rms)	1	degree	3.11			
2.9	Linac Species	H-		4.1			
2.10	Transverse Emittance (95% normalized)	2.5	π-mm-mrad	5.7	5.8		
2.11	Macro Bunch Duty Factor	67	%	5.10	5.12		
2.12	Macro Bunch Frequency	53	MHz	5.12			
2.13	Micro Pulse Length	10.4	uS	5.13			
2.14	Micro Pulse Period	11.1	uS	5.13			

etc…

Project X RD&D Strategy
325 MHz Linac Issues

- No special accelerator physics issues are posed by a 420 MeV linac with this beam intensity.
- Development via the High Intensity Neutrino Source (HINS) program
  - 60 MeV front end demonstration based on scrf
- Technology choices
  - room temperature vs. superconducting
  - Upgrade path
- Beam duty cycle and machine availability requirements push the envelope of any existing H- ion source
- Superconducting triple-spoke accelerating cavity is outside the scope of the HINS program

Project X RD&D Strategy
1300 MHz Linac Issues

- Project X 1.3 GHz linac is based on the ILC cryomodule design.
  - ~40 CMs required for Project X
    - Accommodate cavity gradients in the range 23.6 – 31.5 MeV
  - GDE is developing a standardized CM design as a high priority near-term item, with goal of testing a complete 31.5 MeV/m CM by 2012.
  - ART plan calls for the assembly and testing of several CMs by 2012
  - Fermilab is playing a leading role in CM design, fabrication, and testing
- Project X has same average current as ILC (9 mA$\times$1 msec$\times$5 Hz)
  - Bunch structure is different
  - Beam test addresses significant, but not all, ILC issues.
- Project X construction will require a production rate of ~one cryomodule/month, with a procurement leadtime of <1 year.
  - Supported by SRF infrastructure program
  - Engage industry in a manner that leads to a cost effective design

Project X RD&D Strategy
8 GeV Transfer Line Issues

- Control and mitigation of beam loss due to single particle loss mechanisms in the transport line.
- Uncontrolled losses in the injection region due to the injected and circulating beam interaction with the stripping foil.
- The stripping efficiency and lifetime of the injection foil, or
- The stripping efficiency of a laser stripping injection system.
- The collection of the stripped electrons and neutrals from the injection process.

Project X RD&D Strategy
Ring Issues

- Recycler Ring
  - Space Charge tune shift
  - Electron cloud instabilities
  - Storage efficiency (lifetime)

- Main Injector
  - Space Charge tune-shift
  - Electron cloud instabilities
  - RF Power
  - Beam loading
  - Transition crossing

Project X RD&D Strategy
8 GeV Slow Spill Issues

- Extraction system configuration: chromatic effects on the transverse phase space at the extraction Lambertson
- Lattice requirements
  - existing gradient magnet harmonics,
  - new powered harmonic elements,
  - modifications to the Recycler lattice.
- RF beam structure requirements
- Duty factor
- Speed of the extraction process
- Extraction point location
- Loss mitigation and shielding requirements

Project X RD&D Strategy
Neutrino Beamline Issues

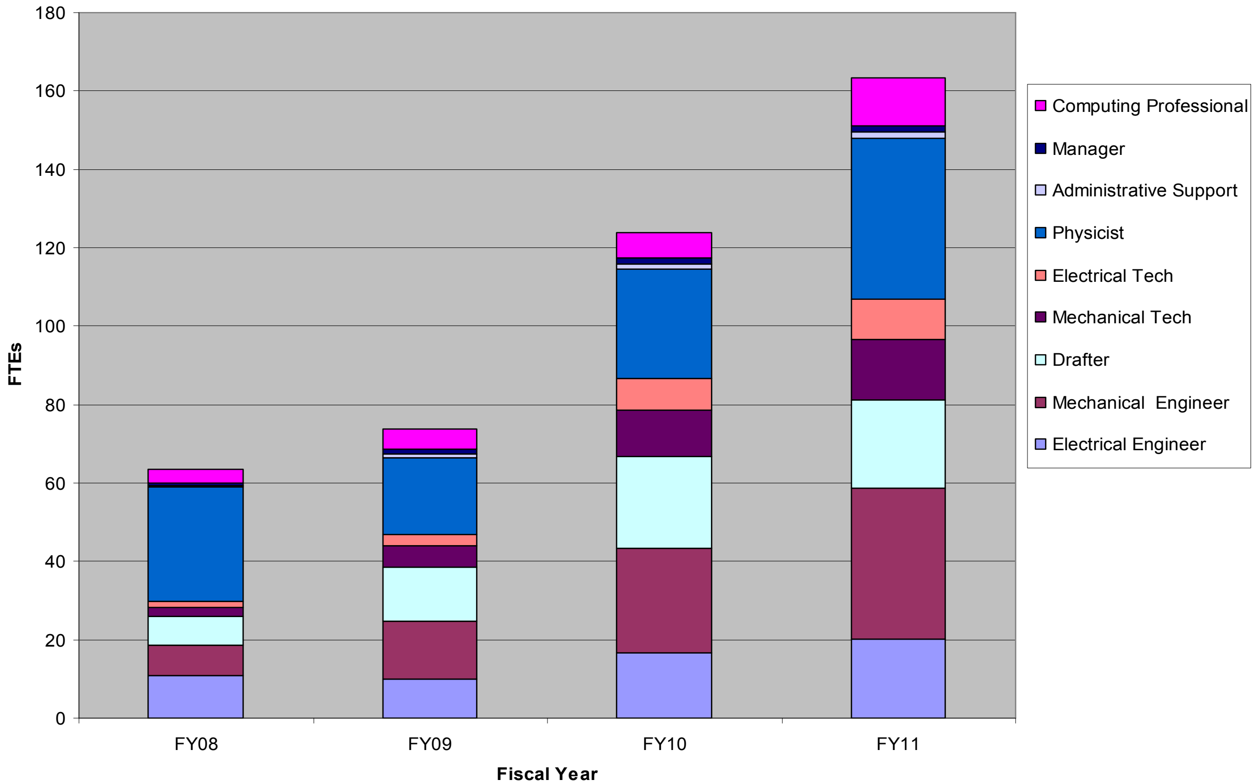
- Development of a proton target and magnetic horn system capable of handling 2.3 MW of beam power at 120 GeV
  - Project X will increase beam power by a factor of 5-6 beyond the original NuMI design.
  - Initial investigation suggest that the NuMI target hall could be upgraded to handle about 1-2 MW of beam power
    - NuMI beamline was conservatively designed,
    - Redundancy in the initial design.
- Reliability, maintainability, and uptime of the NuMI facility.
  - Limits on the decay pipe window
  - Residual radiation, airborne emissions, and ground water protection
  - Handling of radioactive components

Project X RD&D Strategy
Civil Construction Issues

- Existing design concept for Proton Driver facilities meets many Project X requirements
- Wetland mitigation options
- Re-use of existing utility capabilities?
- Re-use of existing cryo facilities?
- Large injection abort
  – Significant civil construction required
- Project X has significant utility infrastructure in common with ILC (power distribution, HVAC, cooling, cryogenics, etc.)
  – Involved Fermilab resident expertise can be shared between the ILC and Project X efforts.

  ⇒ Opportunity for shared development of cost effective designs in these areas.

Project X RD&D Plan
Resource Requirements and Profile



Personnel profile by skills types

Note: This includes total resources, not just Fermilab; Incremental to ILC, SRF, and HINS programs

Project X RD&D Plan
Budget Profile

	Project X R&D Plan Budget Profile					
	(Dollar amounts in millions, fully burdened)					
	FY08	FY09	FY10	FY11	FY12	TOTAL
SWF	$6.7	$10.5	$19.1	$26.3		$62.6
M&S	$1.5	$4.9	$6.2	$13.7		$26.3
TOTAL	$8.1	$15.5	$25.4	$40.0		$88.9
				PED		
	CD-0		CD-1	CD-2/3a		

Project X RD&D budget profile

- Scientists not included
- Can produce this table with any combination of scientists in or out, FY08 or AY$, burdened or unburdened
- Incremental to ILC, SRF, and HINS programs

Project X and ILC/SRF

- Project X initial parameters aligned with ILC requirements
  - 9 mA × 1 msec × 5 Hz
  - 23.6 – 31.5 MV/m
- Industrialization role
  - Project X requires 37 β=1, ILC style cryomodules
  - Production over a two-to-three-year period represents a significant advance over capabilities anticipated in ~2010; however, the production rate is below that required by ILC

  $\Rightarrow$ This activity would represent the initial phase of an industrialization buildup for ILC (in the U.S.).

Project X and ILC/SRF
Joint Development Strategy

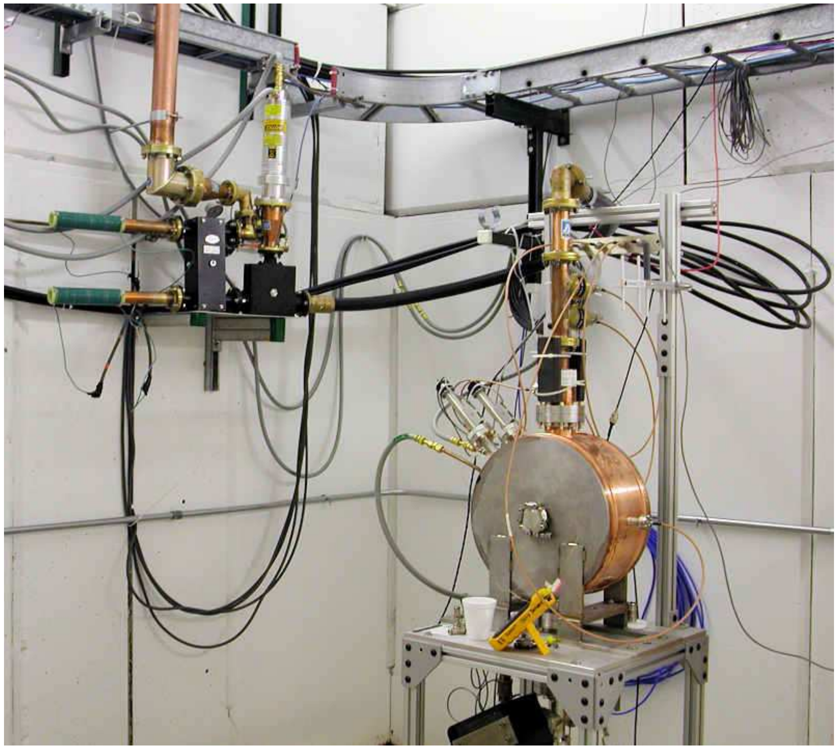
- 1.3 GHz cavity and cryomodule design, fabrication, and testing remains the responsibility of the ILC program over the first few years.
  - There will be single 1.3 GHz development program at Fermilab, supporting the ILC/GDE program and simultaneously understanding Project X requirements.
  - At an appropriate time (before CD-2) the Project X cryomodule design will be developed. The expectation is that it will be similar, but not identical, to the ILC design (including choice of gradient). The design will be compatible with an identified upgrade path.
- The ILC program will also be developing the 1.3 GHz rf source
- Creation of facilities capable of fabricating one cryomodule/month remains the responsibility of the SRF infrastructure program.

Project X and ILC/SRF
Systems Testing at NML

- ILCTA-NML is being constructed under the SRF Infrastructure program to support testing of a complete rf unit.
- Full power test of a complete rf unit would be supported.
- A joint strategy for testing a complete rf unit with beam:
  - Simple thermionic gun + capture cavity (30 MeV) provides correct average current, but not specific bunch structure
  - Up to 2 Hz is possible with current refrigeration system
  - NML building extension is not required
  - $\Rightarrow$ Cost reduction of ~20% on the NML facility.
- This configuration supports substantial progress toward ILC (S1 and S2) goals: demonstration of stable high-power operations.
- The option for subsequent expansion to match the full suite of ILC goals is preserved through this approach.

Project X and HINS

- The HINS program is developing front end technology beyond the requirements of Project X initial goals:
  - 60 MeV front end @ 27 mA $\times$ 1 msec $\times$ 10 Hz
  - Demonstrate novel technologies for a high intensity non-relativistic linac
    - Multiple room temperature and sc cavities driven by a single rf source (high power vector modulators)
    - High speed (nsec) beam chopping at 2.5 MeV
  - Establish technical feasibility and cost basis by ~2010



Project X and HINS
Joint Development Strategy

- HINS provides a very natural starting point for a Project X upgrade
  - 27 ma × 1 msec × 10 Hz = 2 MW (if accelerated to 8 GeV)
  - Other options: 9 ma × 3 msec × 10 Hz
- Two decisions (prior to CD-2):
  - Do we use HINS as the initial front end or do we utilize a conventional (room temperature) front end?
    - Cost-benefit analysis
  - Can we establish an 8 GeV upgrade path via HINS and if so, how does this impact the 1.3 GHz linac facility design?
- In either case it will be essential to carry the 60 MeV facility through to completion

Project X RD&D Plan

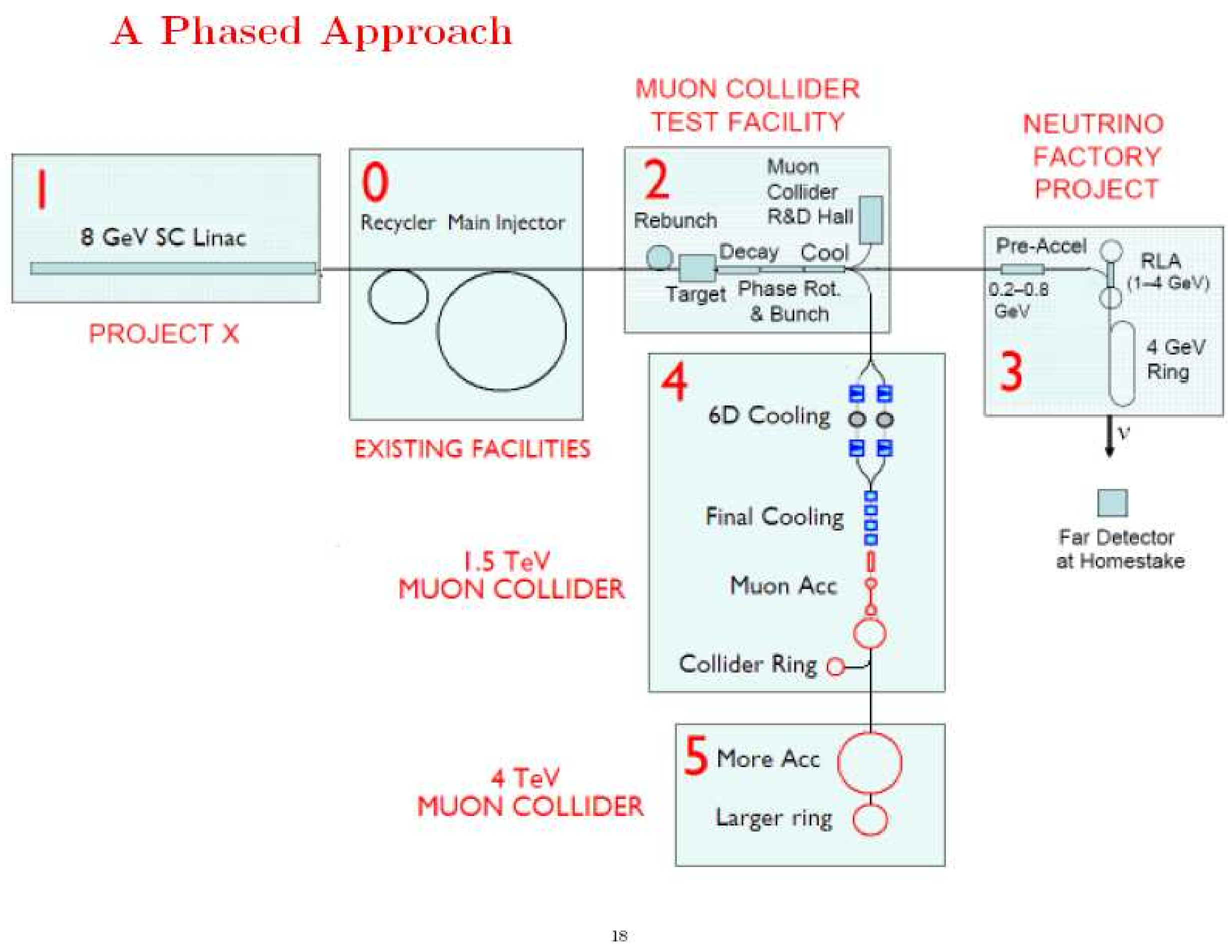
An Integrated Plan

	FY08	FY09	FY10	FY11	FY12	FY13
ILC C+CM	CM1	CM2	CM3 (Type IV)		CM4 rf unit syst.tst	
ILC RF Power		MBK	PFN modulator			
SRF Infra.				NML complete		CAF complete (1 CM/month)
HINS				60 MeV beam tests		
Project X			CDR	FE decision Gradient decision baseline docs	rf unit sys.tst	
	CD-0		**CD-1**	**CD-2/3a**		

Project X and the Muon Program

- Project X shares many features with the proton driver required for a Neutrino Factory or Muon Collider
  - IDS-NF shows 4 MW @ 10± 5 GeV proton energy
  - Muon Collider requires similar power, but requires charge segregated into a single bunch →higher energy?
- Possible utilization of ILC cavities for acceleration in the recirculating linacs
  - Issue is very high bunch population (up to 2×10^{12} in certain MC schemes)
    - Under study at Fermilab
- Natural evolutionary schemes through neutrino superbeams (MN and DUSEL) → Neutrino Factory → Muon Collider
  - (see P5 presentations by Y-K. Kim and R. Palmer)

Project X and the Muon Program
Possible Evolution (Palmer)



Project X and Muon Program

- Next Steps
  - Understand the range of possible performance specifications for a proton driver supporting a Neutrino Factory and Muon Collider (APC)
  - Develop a Project X upgrade performance goal based on NF/MC requirements (plus input from the experimental community)
  - Develop a long term Project X development plan
  - Establish the initial Project X design to be consistent with the long term development plan
  - (Understand the long term implications of utilizing a linac vs sychrotron as the starting point)
  - Do all this in coordination with the NFMCC and MCTF

Project X RD&D Plan
Collaboration Plan

Disclaimer: This is not formally agreed to, although institutions have been invited to comment as this has been developed.

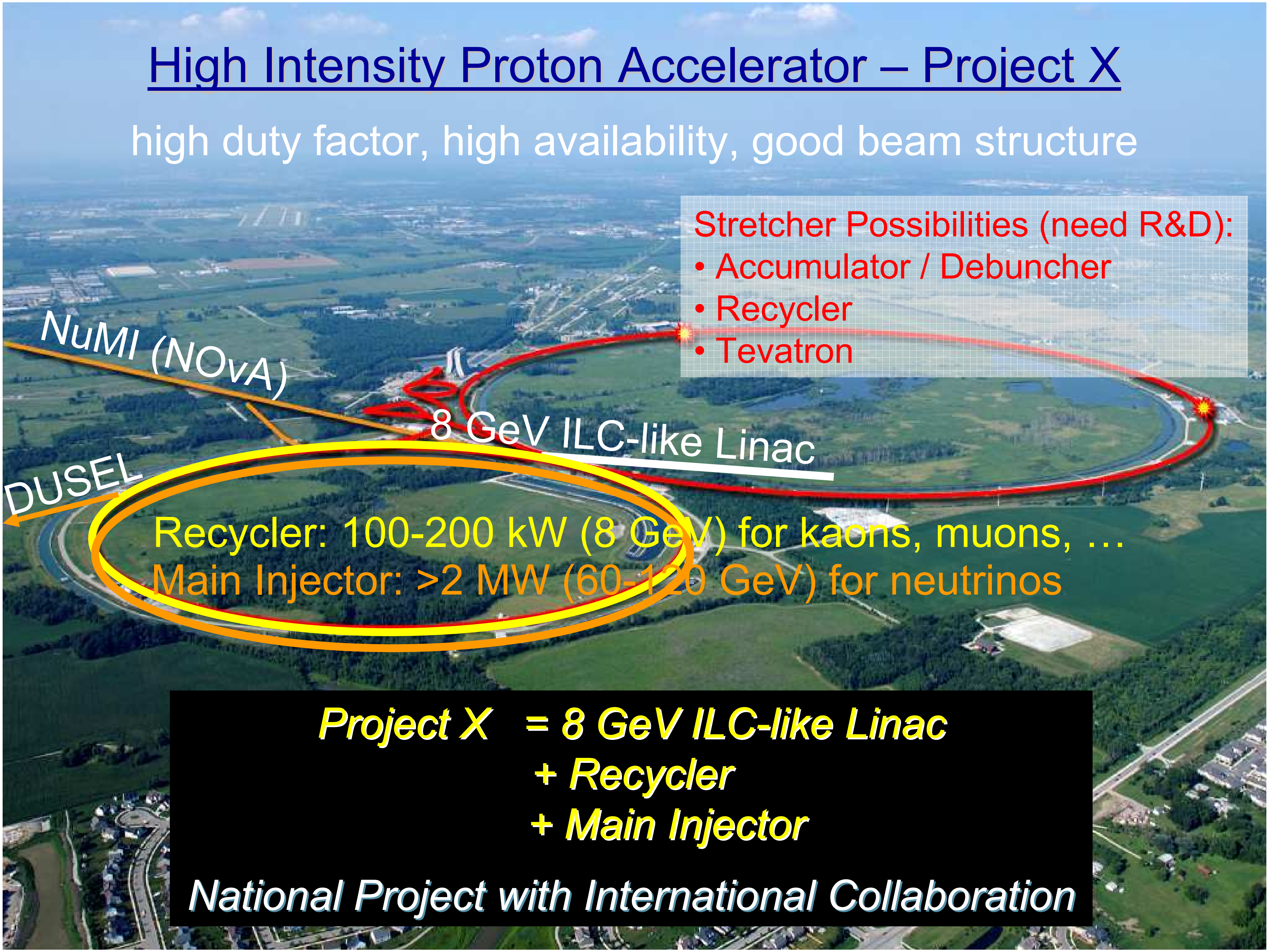
- Intention is to organize and execute the RD&D Program via a multi-institutional collaboration.
  - Goal is to give collaborators complete and contained sub-projects, meaning they hold responsibility for design, engineering, estimating, and potentially construction if/when Project X proceeds.
  - Project X RD&D Collaboration to be established via a Collaboration Memorandum of Understanding (MOU) outlining basic goals of the collaboration, and the means of organizing and executing the work.
  - It is anticipated that the Project X RD&D Program will be undertaken as a "national project with international participation". Expectation is that the same structure of MOUs described above would establish the participation of international laboratories.

Summary

- The Project X design concept supports a long term future for Fermilab based on world leading facilities at the:
  - Energy Frontier
  - Intensity Frontier
- Design concept exists for a facility with >2 MW beam power at 120 GeV, simultaneous with 200 kW at 8 GeV.
  - Major sub-system performance goals established
  - Supports world class program in neutrino physics and rare processes
- Design provides flexibility to support a long-term future for accelerator based physics at Fermilab
  - Potential upgrade paths to mulit-MW at 8 GeV exist
  - Design aligned with needs of ILC technology development
  - Design concept supports future development of muon facilities

Summary

- Project X RD&D plan developed covering the period through CD2 (2011)
  - Integrates effort on Project X, ILC, and HINS
  - Resource plan exists
  - Team forming under the leadership of Dave McG.
- Working towards organizing as a national project with international participation.


High Intensity Proton Accelerator – Project X
high duty factor, high availability, good beam structure
Stretcher Possibilities (need R&D):
• Accumulator / Debuncher
• Recycler
• Tevatron
NuMI (NOvA)
8 GeV ILC-like Linac
DUSEL
Recycler: 100-200 kW (8 GeV) for kaons, muons, …
Main Injector: >2 MW (60-120 GeV) for neutrinos
Project X = 8 GeV ILC-like Linac
+ Recycler
+ Main Injector
National Project with International Collaboration